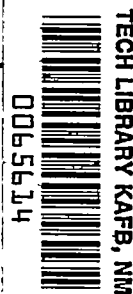# NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

TECHNICAL NOTE 2437

SOME MEASUREMENTS OF THE EFFECT OF GASEOUS IMPERFECTIONS

ON THE CRITICAL PRESSURE RATIO IN AIR

AND THE SPEED OF SOUND IN NITROGEN

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SUMMARY

Experiments were made to measure the speed of sound in nitrogen at room temperatures in the pressure range of 0 to 2000 pounds per square inch, and the critical pressure ratio of air expanded isentropically from stagnation conditions in the same range. The experimental results were then compared with the values obtained by using the Van der Waals equation and the Beattie-Bridgeman equation.

The speed of sound, as measured, agreed within 1.5 percent with that predicted by the Beattie-Bridgeman equation and within 4 percent with that predicted by the Van der Waals equation over the entire test range. The measured critical pressure ratio agreed with that predicted by the Beattie-Bridgeman equation within the experimental accuracy of the tests and with that predicted by the Van der Waals equation within 1 percent.

INTRODUCTION

Equations for the isentropic flow of an imperfect gas obeying Van der Waals' equation were developed in reference 1. For most purposes, the effects of gaseous imperfections were found to be small; therefore, the use of Van der Waals' equation for the prediction of these effects would be desirable because of its simplicity. Several other methods have been published using more complicated and more accurate equations of state to represent the imperfections of a gas. Probably the most accurate method is that presented in reference 2, in which the gaseous imperfections are represented by the Beattie-Bridgeman equation. The method, however, is far more laborious than the method of reference 1. The purpose of this investigation was to measure the speed of sound and the initial pressure ratio over a wide range of pressures and to compare the experimental data with the values predicted by the Van der Waals and Beattie-Bridgeman equations.

Imperfect-gas effects may be large at the high stagnation pressures contemplated in wind tunnels at hypersonic Mach numbers where it is desirable to simulate as closely as possible the flight Reynolds number. Stagnation pressures up to 2000 pounds per square inch absolute in the range of 500° F to 1500° F absolute are of interest in this work. Within this range, large effects resulting from gaseous imperfections are encountered at low stagnation temperatures and high stagnation pressures. On the other hand, the effect of these forces is much smaller at the high stagnation temperatures throughout the whole range of pressures. Further, the effects of vibrational heat capacity at 1500° F absolute are of opposite sign to the Van der Waals forces, so that isolation of the imperfect-gas effects is difficult. These tests were therefore limited to measuring the effects of forces of the Van der Waals type at a stagnation temperature near 500° F absolute. The speed-of-sound measurements were made in nitrogen at pressures up to about 2000 pounds per square inch absolute, and the critical-pressure-ratio measurements were made in air at pressures up to 1800 pounds per square inch absolute.

SYMBOLS

a   Van der Waals constant (table I)

a'   Beattie-Bridgeman constant (table I)

A_0 Beattie-Bridgeman constant (table I)

b   Van der Waals constant (table I)

b'   Beattie-Bridgeman constant (table I)

B_0 Beattie-Bridgeman constant (table I)

c   Beattie-Bridgeman constant (table I)

c speed of sound in gas

C_1 speed of sound in perfect gas

e_1 Beattie-Bridgeman function $\left(B_0 - \dfrac{A_0}{RT} - \dfrac{c}{T^3} \right)$

e_2 Beattie-Bridgeman function $\left(-b'B_0 + \dfrac{a'A_0}{RT} - \dfrac{cB_0}{T^3}\right)$

e_3 Beattie-Bridgeman function $\left(\dfrac{b'cB_0}{T^3}\right)$

R universal gas constant

T temperature

V specific volume

γ ratio of specific heats

γ_1 ratio of specific heats in perfect gas

ρ mass density of gas

APPARATUS AND METHODS

The two most important parameters involved in aerodynamic phenomena that should be predicted accurately by any theory developed for the imperfect-gas effects in a flowing gas and that might also be easily measured are the speed of sound in the gas at a given temperature and pressure and the ratio of local pressure to stagnation pressure for a given local Mach number. The first parameter is a measure of the most important random property of a gas from considerations of gas dynamics, whereas the second parameter is a measure of the pressure ratio necessary to convert a certain amount of random kinetic energy to directed kinetic energy.

Two completely different sets of tests, therefore, were made in apparatus specifically designed for the purpose of measuring each of these quantities. The speed of sound in nitrogen at approximately room temperature with pressures from 0 to 2000 pounds per square inch absolute was measured and compared with theoretical values. The critical pressure ratios for air expanded to Mach number 1 were measured for stagnation pressures of 0 to 1800 pounds per square inch absolute at stagnation temperatures of about 500° F absolute. Nitrogen rather than air was selected for the measurement of the speed of sound to preclude the oxidation hazard, since there was no assurance that the apparatus could be maintained free of oil.

Measurement of the Speed of Sound

The speed of sound in a gas at high pressures was measured by the use of an acoustical interferometer designed especially for high pressures. The apparatus is shown in figure 1.

A carefully cut quartz crystal which produced undistorted ultra-sonic waves was mounted in one end of a cylindrical steel chamber facing a movable reflector plate. The crystal holder and reflector plate were covered with felt except for an area in the center approximately the size of the end of the crystal. This arrangement insured that only those waves which had traveled in a straight path between the crystal and the reflector plate were allowed to affect the crystal. The reflector plate, mounted on a threaded shaft, was moved relative to the crystal by a hand wheel on the external end of the shaft. The hand wheel was accurately calibrated to show the position of the reflector plate. A ball-bearing joint was installed in the shaft to prevent the reflector plate from rotating when the hand wheel was turned.

The crystal was excited at its natural frequency (49,600 cps) by a standard signal generator (fig. 2). The 0.5-volt output of the generator was amplified to 800 volts before transmission to the crystal. A voltmeter measured the output of the amplifier unit and, hence, the power absorbed by the crystal. The voltage fluctuations indicated by this voltmeter as the reflector plate was moved could thus be used to determine the positions of the reflector plate for which the crystal was alternately in and out of resonance. Thus, the distance moved by the reflector plate between successive peaks of the voltmeter readings was equal to one-half the wave length of the sound signal generated by the crystal.

The frequency of the signal was measured by a frequency meter and an oscilloscope. The output of the generator and the frequency-meter output were both put into the oscilloscope, and when the resultant pattern on the oscilloscope was stationary, the frequency was read on the meter.

The temperature of the gas in the test chamber was measured by a copper-constantan thermocouple located near the crystal.

Pressure was regulated by three high-pressure valves located between the high-pressure line and the chamber (fig. 1). A pressure gage was attached opposite the inlet valves. Graphite packing was used in all packing glands and was found to hold pressure up to 2000 pounds per square inch absolute for a short time. Frequent repacking was necessary.

All electrical equipment was allowed to warm up before tests were started to insure constant conditions during testing. Nitrogen was then admitted from the supply tank, and the pressure was adjusted by means of the valves. The valves were closed during tests.

Temperature and frequency were noted frequently during tests. Very little change in either was observed. The wave length was determined by showing the change in position of the reflector plate for successive maximum voltmeter readings for the range of movement of the reflector plate. Numerous readings were taken at each pressure. These readings were averaged to find an average value of the wave length. In the range of these tests the apparatus was believed to be free of dispersion effects since the temperature of the nitrogen in the test chamber was below that required to excite the vibrational degrees of freedom of the molecules and the frequency of the crystal was too low to cause a lag in the adjustment of the rotational degrees of freedom of the molecules.

The apparatus was such that it was able to repeat results to within 0.5 percent. The thermocouple was checked and found to be accurate to within 1° F. The frequency meter was found accurate to within 0.005 percent. The calibration of the hand wheel was accurate to within 0.1 percent. The over-all accuracy of the system, therefore, may be expected to be very good. Extreme care must be taken, however, in elimination of interference effects in the test chamber. Surrounding the crystal holder and the edges of the reflector plate with felt was found to be necessary for accurate, consistent readings. Any small leak in the system caused inaccurate readings because of the effects of the circulating air.

Measurement of the Critical Pressure Ratio

In order to measure the critical pressure ratio, a small, very-high-pressure settling chamber and nozzle were constructed as shown in figure 3. The air supply for this apparatus consisted of 30 ordinary compressed-air bottles which were charged with dry air to a pressure of 2200 pounds per square inch absolute and connected to a common manifold, which was, in turn, connected by a high-pressure valve to a settling chamber. This apparatus is shown schematically in figure 4. The nozzle was so constructed that at the minimum section the pressure on the center line of the nozzle blocks and at the center line of the side walls could be measured by calibrated high-pressure gages. The settling-chamber pressure was measured in the same way, and the settling-chamber temperature was measured by a thermocouple.

Tests were run by opening wide the main valve after all the bottles had been opened onto the common manifold. The stagnation pressure and pressures about the minimum section of the nozzle, as well as the stagnation temperatures, were recorded photographically at intervals as the pressure in the settling chamber decreased.

Because the nozzle was small and the rate of discharge of the air bottles therefore very low, the stagnation temperature during any one run had a negligible variation.

The critical pressure ratio was obtained by averaging the pressures on the center line of the side walls of the nozzle with that on the center line of the nozzle blocks between the two walls.

RESULTS AND DISCUSSION

Speed of Sound

The ratio of the speed of sound in nitrogen, as measured at a temperature of $545°$ F absolute, to the speed of sound in a perfect gas is plotted against stagnation pressure in figure 5. These data are compared with theoretical results obtained both by the Van der Waals equation (reference 1)

$$\left(\frac{c}{c_1}\right)^2 = \frac{v^2}{(v-b)^2} - \frac{2a}{\gamma_1 RTv}$$

and by the Beattie-Bridgeman equation (reference 2)

$$\left(\frac{c}{c_1}\right)^2 = \frac{\gamma}{\gamma_1}\left(1 + 2e_1\rho + 3e_2\rho^2 + 4e_3\rho^3\right)$$

In the range of pressures between 0 and 2000 pounds per square inch absolute at $545°$ F absolute, the speed of sound measured was within 4 percent at the point of maximum deviation of that predicted by Van der Waals' equation, the error being largest at 2000 pounds per square inch absolute. The speed of sound, as measured, was within approximately 1.5 percent of that predicted by the Beattie-Bridgeman equation over the entire range of pressures. Some of the discrepancy between experiment and the more exact theory may have been due to experimental error, since in operation the apparatus was not accurate to more than ±0.5 percent.

The remaining small deviation of the experimental data from the Beattie-
Bridgeman equation is not considered to be significant but is possibly
due to some untraceable peculiarity in the characteristics of the experi-
mental apparatus.

Critical Pressure Ratio

The critical pressure ratios measured during a typical run at a
stagnation temperature of 500° F absolute are shown in figure 6 compared
with the theoretical values calculated by the Van der Waals equation
from reference 1 and with the more exact theoretical values calculated
by the Beattie-Bridgeman equation of reference 2.

In the range of stagnation pressures between 0 and 1800 pounds per
square inch absolute the critical pressure ratio, as measured, was
within 1.0 percent over the entire range of that predicted by Van der
Waals' equation. The critical pressure ratio measured agreed even
better with that predicted by the Beattie-Bridgeman equation.

CONCLUSIONS

Measurements have been made of the speed of sound in nitrogen at
545° F absolute at pressures between 0 and 2000 pounds per square inch
absolute and of the critical pressure ratio in air at 500° F absolute
at pressures between 0 and 1800 pounds per square inch absolute.

The speed of sound, as measured, agreed within 1.5 percent through-
out the entire range with that calculated by the Beattie-Bridgeman
equation of state and within 4 percent over the same range, although
the greatest error occurred at the highest pressures, with that predicted
by the Van der Waals equation of state.

The critical pressure, as measured, agreed within the experimental
error with that calculated by the Beattie-Bridgeman equation and agreed

within 1.0 percent over the entire range tested with that predicted by
the Van der Waals equation of state.

Langley Aeronautical Laboratory
     National Advisory Committee for Aeronautics
          Langley Field, Va., May 14, 1951

REFERENCES

1. Donaldson, Coleman duP.: Note on the Importance of Imperfect-Gas
     Effects and Variation of Heat Capacities on the Isentropic Flow
     of Gases. NACA RM L8J14, 1948.

2. Crown, J. C.: Flow of a Gas Characterized by the Beattie-Bridgeman
     Equation of State and Variable Specific Heats; Part I, Isentropic
     Relations. Naval Ordnance Lab. Memo. 9619, April 22, 1949.

TABLE I

CONSTANTS FOR USE IN THE IMPERFECT-GAS EQUATIONS

[The following units are used: pressure in lb/sq ft,
density in slugs/cu ft, and temperature
in $^{\circ}$F abs.]

Constant	Nitrogen	Air
a	8.36×10^5	8.76×10^5
a'	0.286	0.309
A_o	6.2×10^5	7.05×10^5
b	0.65	0.654
b'	-0.257	-0.176
B_o	0.691	0.738
c	5.23×10^6	4.05×10^6

1 High-pressure valves
2 High-pressure line
3 Thermocouple lead
4 Power to crystal
5 Reflector plate
6 Pressure gauge
7 Hand wheel
8 Crystal
9 Felt
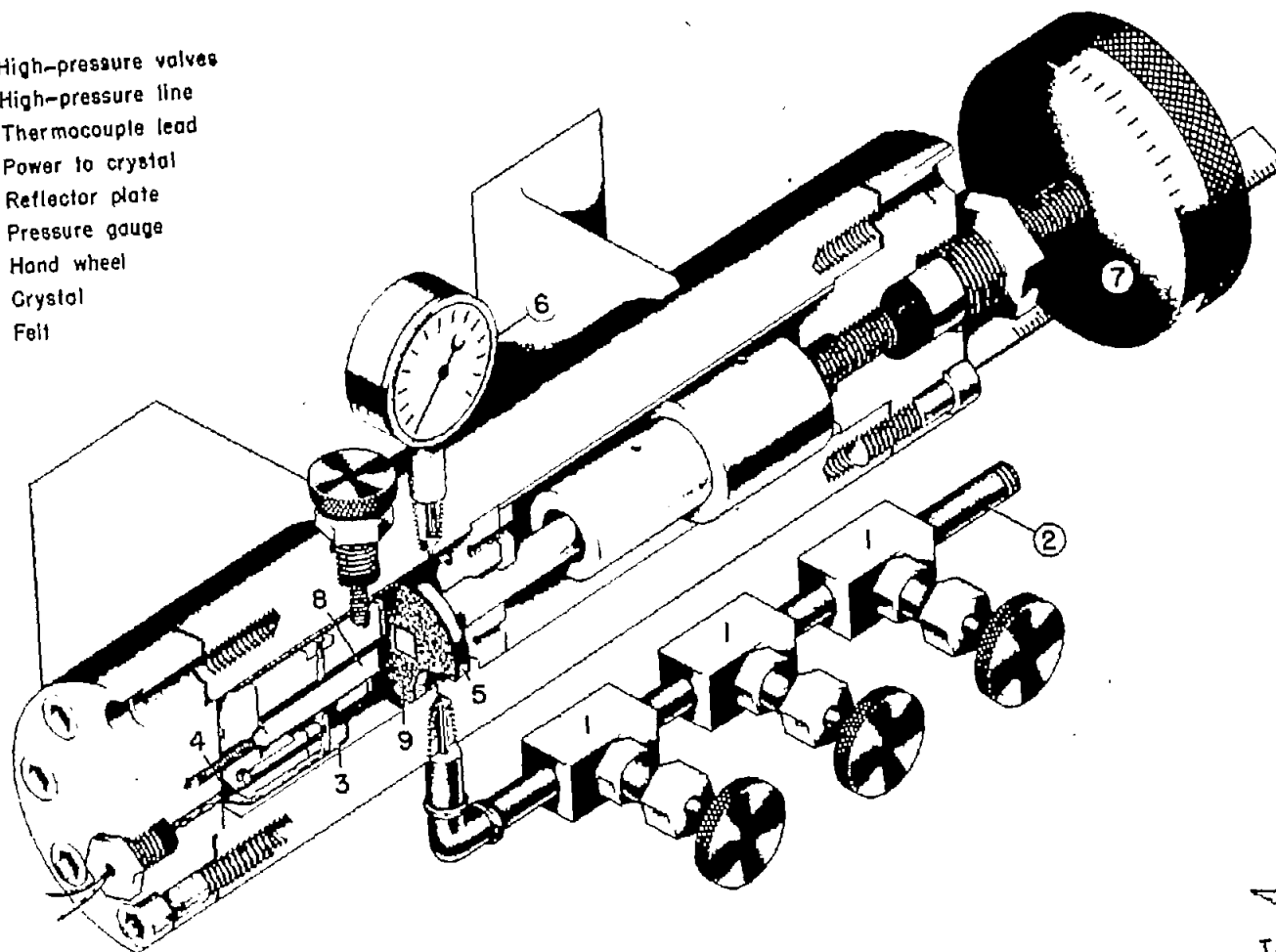
Figure 1.- Pictorial view of acoustical interferometer.

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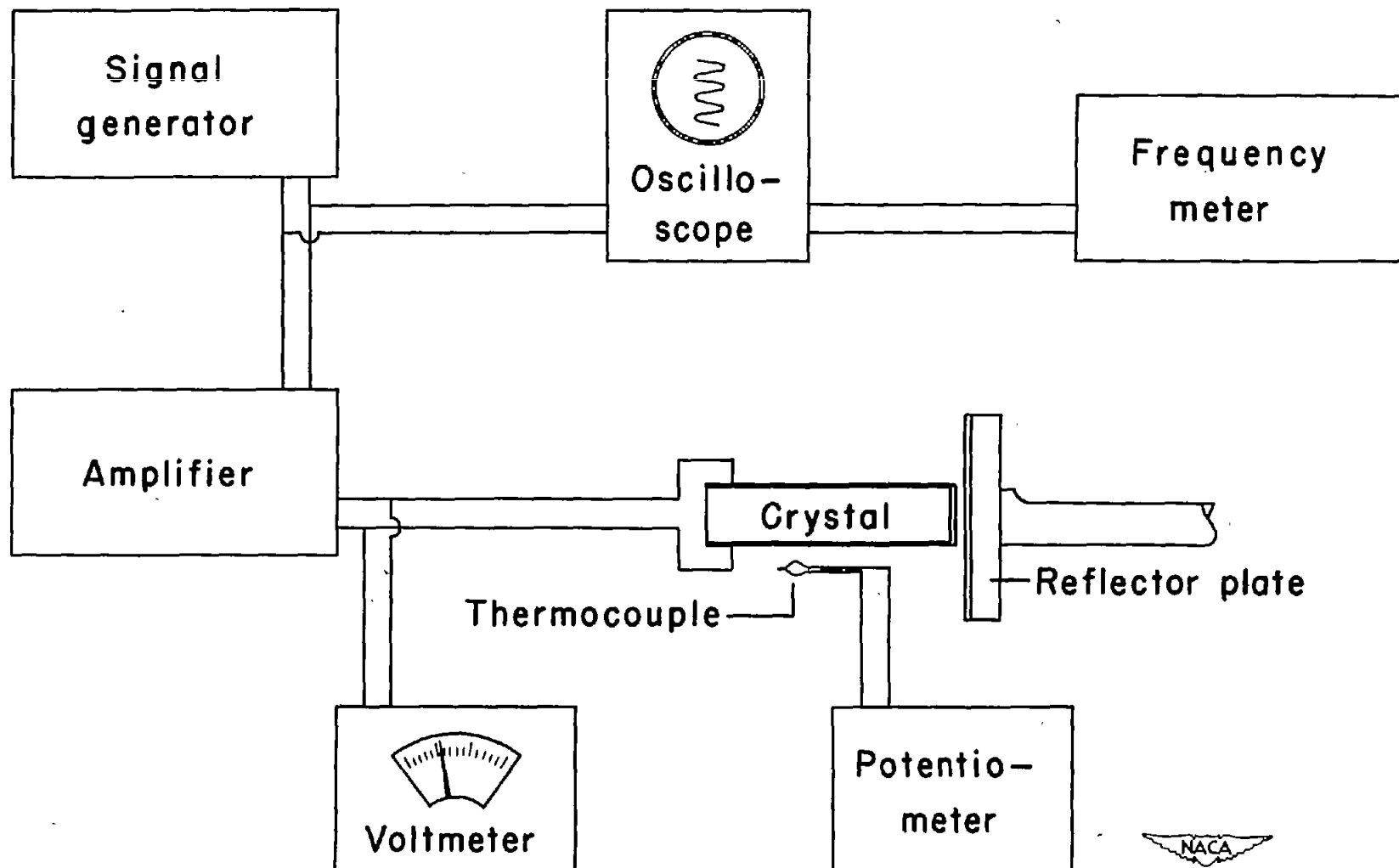
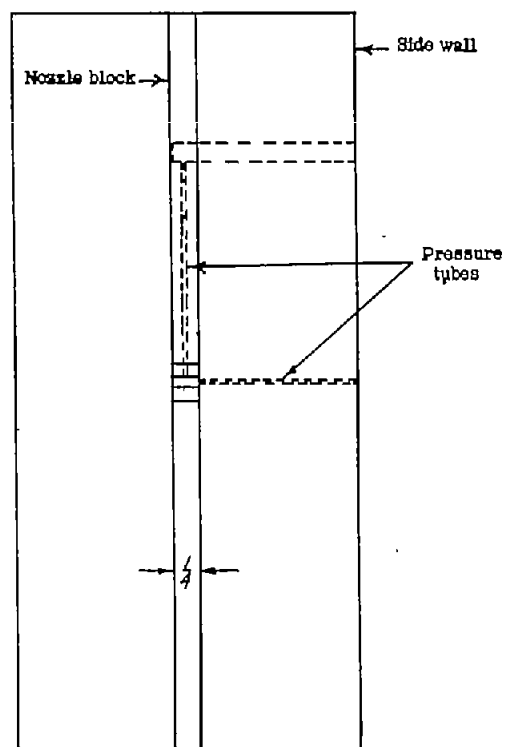Figure 2.- Schematic diagram of electrical system for acoustical interferometer.
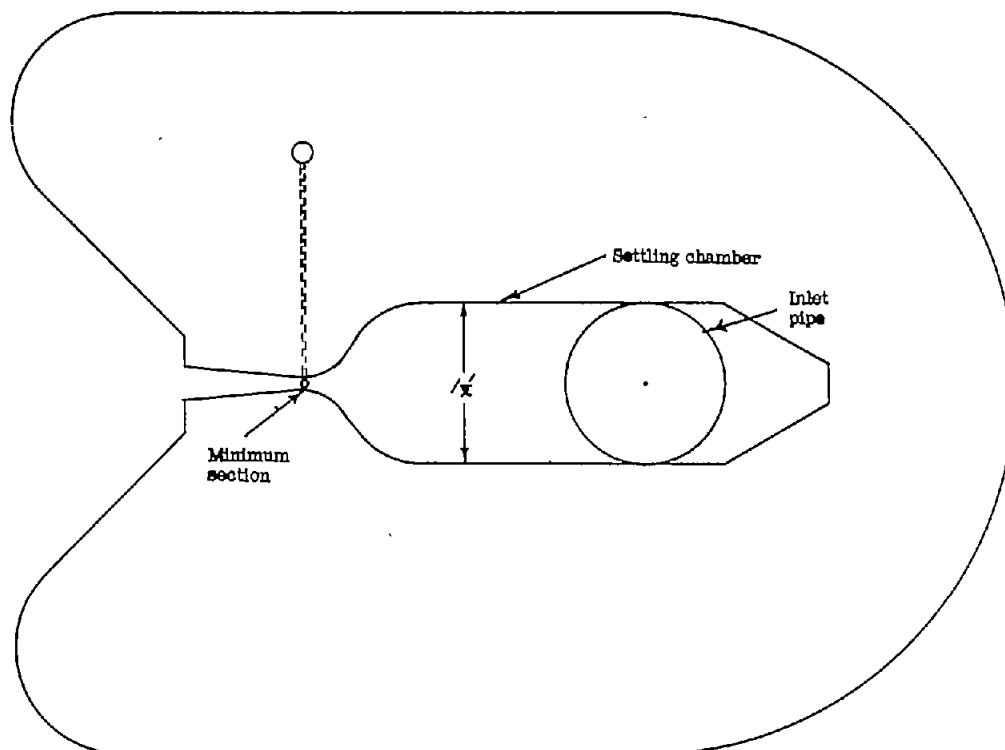
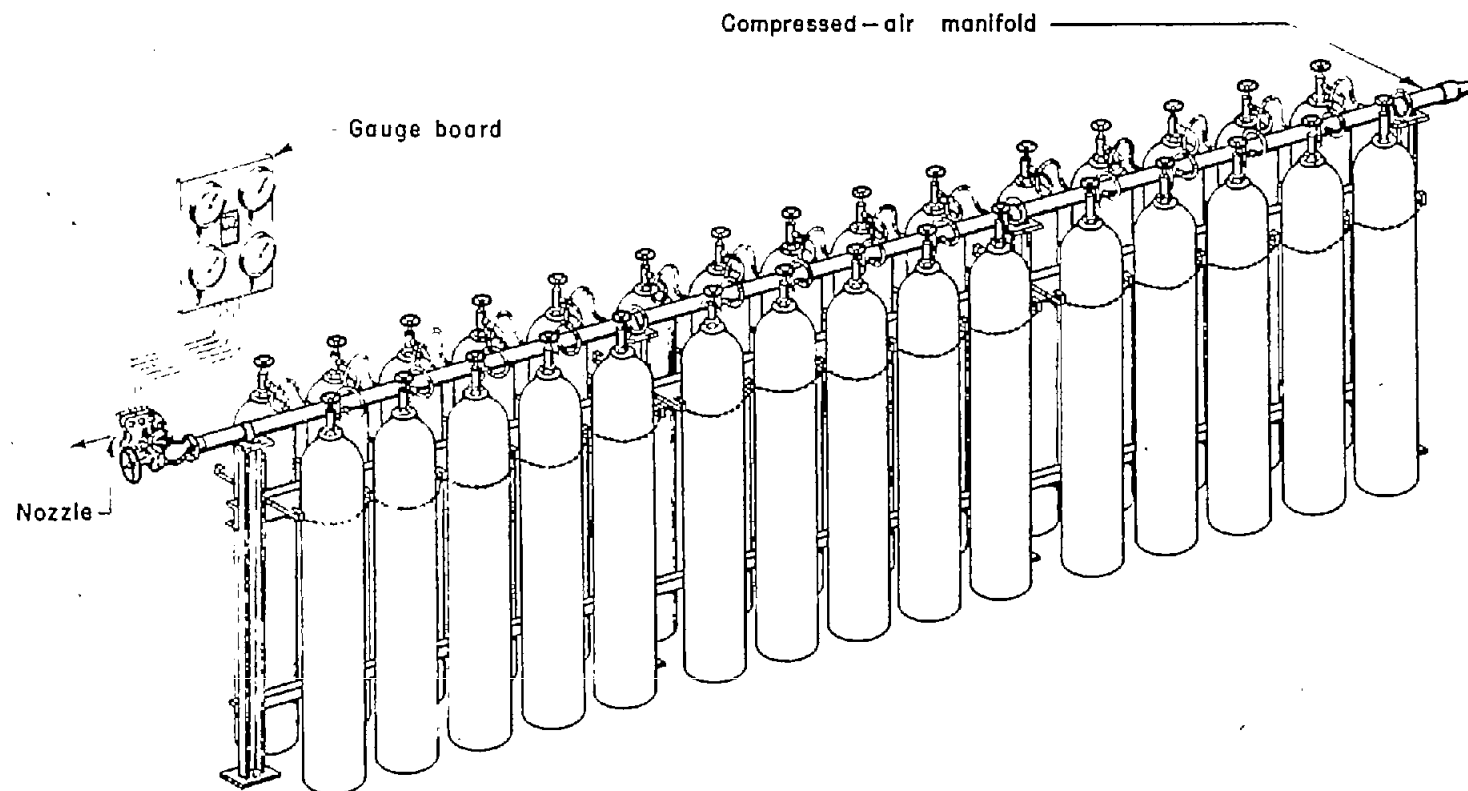Figure 3.- Sketch of nozzle used for measuring critical pressure ratio.

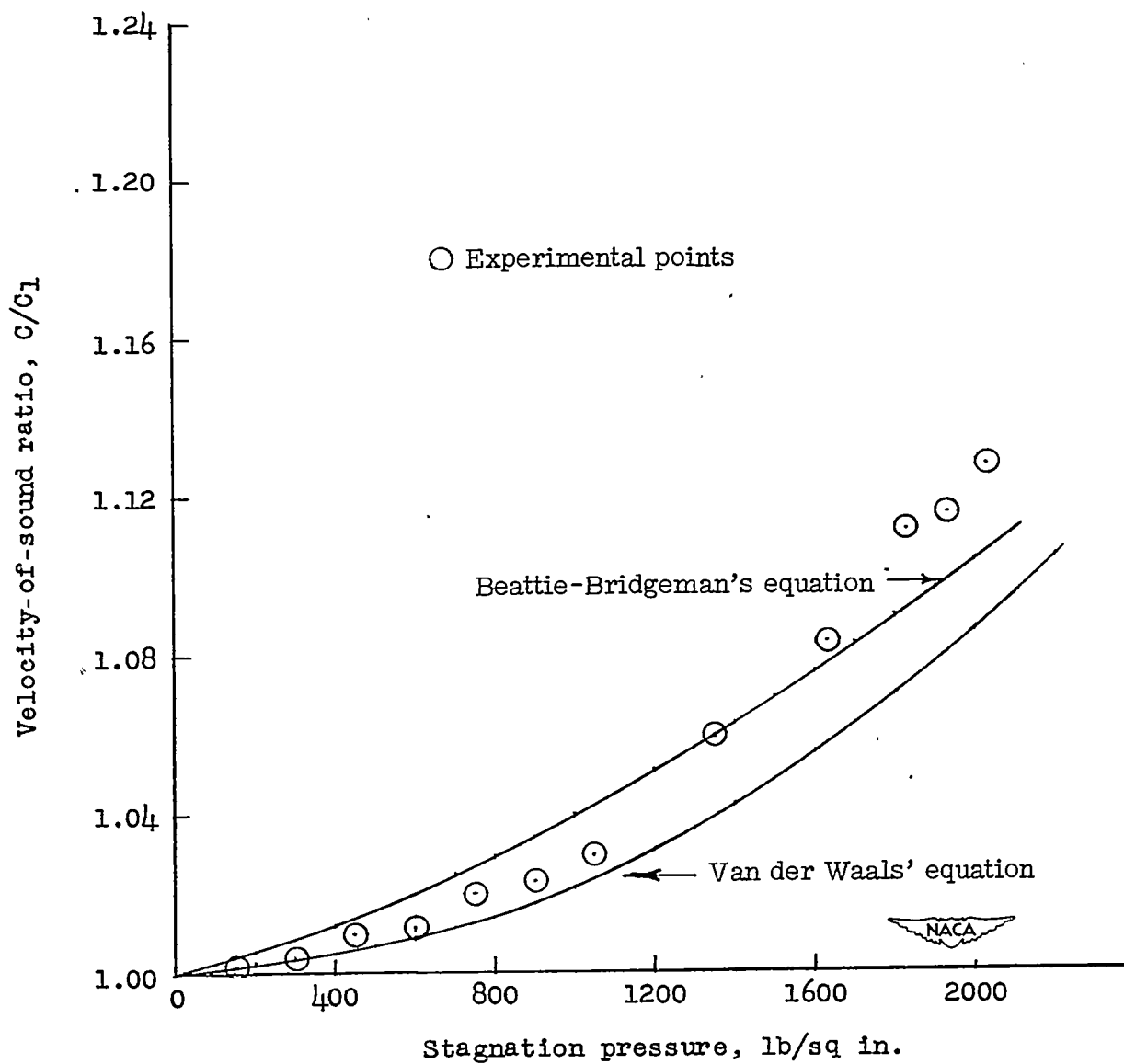Figure 4.- Apparatus for measuring the critical pressure ratio.

Figure 5.- Velocity-of-sound ratio for stagnation temperature
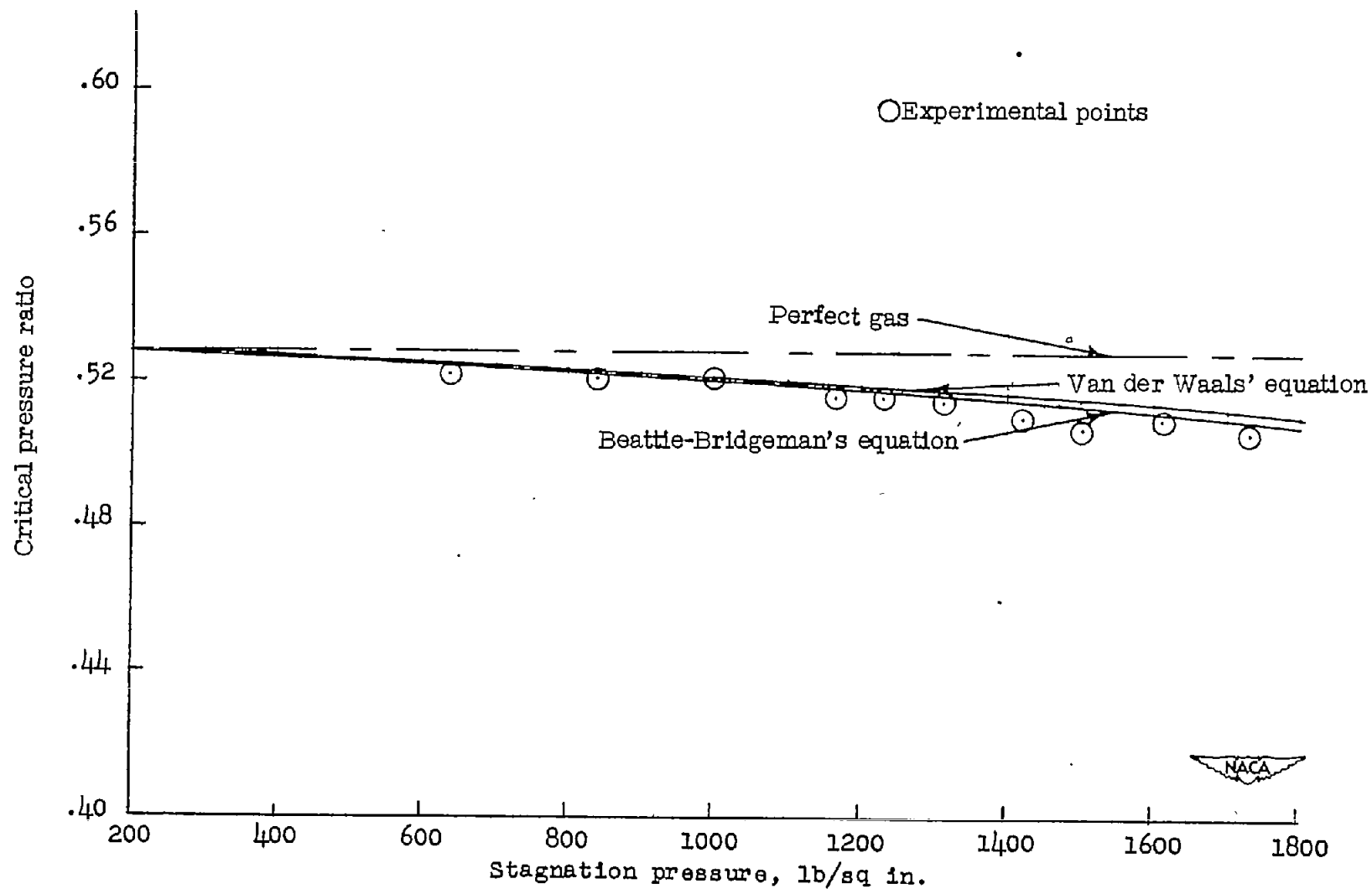of 545° F absolute.

Figure 6.- Critical pressure ratio for stagnation temperature of 500° F absolute.